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WAR METALLURGY DIVISION

Progress Report

on

EFFECT OF LOCKED UP STRESSES ON BALLISTIC PERFORMANCE OF WELDED ARMOR (OD-106): INVESTIGATION OF THE STRESS DISTRIBUTION ACROSS THE THICKNESS OF WELD

by

JOHN T. NORTON, D. ROSENTHAL, AND S. B. MALOOF
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

OSRD No. 4355

Serial No. M-392

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November 24, 1944

November 24, 1944

To: Dr. James B. Conant, Chairman
National Defense Research Committee of the
Office of Scientific Research and Development

From: The War Metallurgy Division (Div. 18), NDRC

Subject: Progress Report on "Effect of Locked Up Stresses on Ballistic Performance of Welded Armor (OD-106): Investigation of the Stress Distribution across the Thickness of Weld".

The attached progress report submitted by John T. Norton, Technical Representative on NDRC Research Project NRC-53, has been approved by representatives of the War Metallurgy Committee in charge of the work.

This report presents the results of an X-ray study of the residual stress pattern across the thickness of a weld in low carbon steel plate.

I recommend acceptance as a satisfactory progress report on the work under Contract OEMsr-877 with the Massachusetts Institute of Technology.

Respectfully submitted,

Clyde Williams

Clyde Williams, Chief
War Metallurgy Division, NDRC

Enclosure

PREFACE

This report is pertinent to the problems designated by the War Department Liaison Officer with NDRC as OD-106, and to the project designated by the War Metallurgy Committee as NDRC Research Project NRC-53.

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Effect of Locked Up Stresses on Ballistic

Performance of Welded Armor

Progress Report

on the

INVESTIGATION OF THE STRESS DISTRIBUTION

ACROSS THE THICKNESS OF WELD

by

J. T. Norton, D. Rosenthal and S. B. Maloof

Massachusetts Institute of Technology

Cambridge, Massachusetts

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Progress Report

on the

INVESTIGATION OF THE STRESS DISTRIBUTION

ACROSS THE THICKNESS OF WELD

NDRC Research Project NRC-53

by J. T. Norton, D. Rosenthal and S. B. Maloof

Summary

The present progress report is concerned with a preliminary investigation undertaken in accordance with the following recommendation of the Project Advisory Committee, p. 27, Final Report, Part I, OSRD No. 3580, April 18, 1944.

No. 4. Make a detailed study of the residual stress pattern through the thickness of the plate in the neighborhood of the weld, using the welded armor as well as low carbon plate which is better suited to the X-ray method.

The investigation has been limited to a low carbon weld for which satisfactory x-ray stress determinations could be made. While not necessarily representative of the stress situation existing in the armor weld, the results are interesting in revealing a marked skin effect in the distribution of residual stress across the thickness of weld. They also show the usefulness of combining information secured by x-ray and wire gage measurements according to a method worked out at this laboratory.

Introduction

It has been shown in our previous report, OSRD No. 3580, p. 15, that the welding operation sets up a restraint not only between the weld and base metals, but also between the layers of the weld itself. Therefore, by cutting loose a block of weld having the full thickness of the plate, a complete relaxation of stress will not be achieved. As a rule, additional relief of stress will take place when slicing the block through the thickness.

The purpose of the present report is to show how this additional information can be used to determine the distribution of the residual stress remaining in the welded blocks across the thickness.

<u>Outline of Experimental Procedures</u>

A. <u>Specimens</u>. The specimens consisted of two blocks of weld, marked Nos. 8 and 11 respectively, supplied through the courtesy of Dr. F. Jonassen, to whom we are indebted also for the information regarding their origin.

Both welds were deposited with the same type of electrode, namely 5/32" class 6010 for the first pass on top and bottom of the plate, and 1/4" type 6012 for the second and third passes on both top and bottom of the plate, using a double "V"-edge preparation. The block marked No. 11 was removed from a panel welded with a step back cascade procedure, whereas the block marked No. 8 was taken from a panel welded in continuous layers from one end of the panel to the other. These panels are referred to in the Progress Report, OSRD No. 3693 of the California Project NRC-64, as panels Nos. 16 and 19 respectively. The blocks served to determine the strain relieved in the direction of weld. They were called for brevity longitudinal blocks.

The shape of these blocks as delivered was quite irregular. For the purpose of further measurements they had to be machined in the form of narrow rectangular prisms. The exact dimensions of the blocks were as follows after machining:

No. 8	1.75 x 0.5 in.	1" thick
No. 11	1.8 x 0.61 in.	1" thick

B. Inspection of the weld metal. In the course of the experiment it appeared necessary to check the soundness of the metal throughout the thickness. Radiography and macro-etching were used for this purpose.

A standard radiographic picture was taken using 130 Kv. - 8 mA - 36" film to tube distance, and a fine grained type of film, the Dupont film No. 506.

The macroetching was carried out on successive sections of weld made for the purpose of stress measurement. Ten per cent nital etch was quite satisfactory in revealing the particulars of structure and defects present in weld.

C. Determination of residual stress across the thickness. Three different methods were used to determine the stress distribution across the thickness of weld. The first method consisted merely of making x-ray diffraction stress measurements on the lateral face of the block No. 11 according to the technique described in our above mentioned report OSRD 3580. As for the two other methods, they were derived from a technique developed at this laboratory and are described in the Appendix in more detail. Briefly speaking, they compute the amount of residual stress at various depths below surface from the change of wire gage readings on the top and bottom surface of the block produced by splitting and successive slicing of the latter. In the first of these methods the strain gage readings alone are used for the computation, whereas in the second, additional x-ray measurements of stress are made on the new sections formed by slicing. Both methods are supposed to give identical results, if the influence of stress, which is left after the block has been split in two, becomes negligible in the thickness direction.

Results

A. Inspection of the weld metal. The radiographic inspection of the block No. 8 revealed a great deal of porosity in the weld. The block No. 11 also showed some porosity, especially in the upper layer; moreover a substantial lack of fusion was noticeable in the first layer.

These two types of defects appeared likewise in the successive sections made through the thickness, when using 10% nital etch. A third type of defect, not disclosed by the radiographic inspection, was found, however, in block No. 8, 0.2" below the top surface. It consisted of small cracks, which could be properly called flakes, Figure 1. They disappeared after some additional 0.006" was removed from the surface by etching.

It is well to point out at this moment that these particulars are given not as an appraisal of the quality of the weld, but as a possible explanation of some anomalies encountered in the measurement of stress.

B. Residual stress pattern across the thickness.

1. The values of stress found by means of x-rays on the lateral face of the block No. 11 are represented by full circles in the diagram, Figure 2. These stresses were measured at points 1, 2, and 3 marked on the side sketch, Figure 2. They turned out to be all compressive stresses of

the same order of magnitude, about 15,000 p.s.i. Because of the obvious discrepancy of those measurements with those described below, no other points of the face were investigated.

2. The residual stress pattern computed from the wire gage readings on top and bottom face, according to the technique described in Appendix, Section 1, is represented by continuous lines in diagrams, Figures 2 and 3 for the blocks No. 11 and 8 respectively. The dashed portion of these lines has been obtained by means of extrapolation assuming end values as given by the third, "combined" method to be described shortly. Both diagrams are fairly well balanced owing to the presence of a high compression on the top and bottom faces of the weld. This compression appears to be of a rather superficial nature, for it drops to zero at less than 0.05" from the surface. The stress over the remaining part of the block is of a much smaller magnitude, especially in the block No. 8. The stress pattern in block No. 11 is not only of a greater magnitude than that in the block No. 8, but also it shows a greater dissymmetry. It is seen that the peaks and valleys are more pronounced on the bottom side, which was the last to be welded, than on the top side of this block.

3. The combined method, consisting of x-ray and wire gage measurements, was used* to compute stresses represented by open circles in diagrams, Figures 2 and 3. The diameter of the circles shows the limit of the probable error (± 2000 psi). Because of the presence of defects only a limited number of points were investigated in sections made across the

* According to the technique described in Appendix, Section 2.

thickness. In block No. 11, the combined method was used only for the two surfaces, but on block No. 8, it was also used for several interior points on the bottom half of the block.

Discussion of the Results

The results plotted in the diagrams, Figure 2 and 3 may be discussed from two points of view: a) The methods of stress measurement, and b) The residual stress pattern.

A. The methods of stress measurement. According to the diagram, Figure 2, a marked discrepancy not only of value, but also of sign exists between the stresses measured directly by means of x-rays, full circles, and the stresses computed from wire gage readings, continuous line. To account for this discrepancy it must be remembered that the x-rays measure the value of stress at a point of the surface, whereas the wire gage readings are used to compute the value of an average stress in a slice of metal removed in the process of successive slicings as described in Appendix, Section 1. There is good reason to believe that the stress on the lateral face of the block is not the same as the average stress in the slice of metal considered. Hence, the results of the two methods cannot be expected to be the same. As a matter of general conclusion, the direct method of measurement by means of x-rays alone cannot solve the problem of stress distribution, if there is a marked stress gradient in the direction normal to the face explored by the x-rays.

On the other hand, the use of the wire gage readings, according to the method explained in the Appendix, gives a picture of the stress distribution which is consistent with the requirements of the balance of stress through the thickness, as shown by the continuous lines in Figures 2 and 3. But this method alone is unable to furnish the value of stress at the top and bottom face of the block, except by means of extrapolation. On the contrary, the x-ray method measures this stress directly and without any ambiguity. Hence, there is real advantage in combining the two methods of measurement.

In addition to the end points of the diagrams, Figures 2 and 3, the combined method of x-rays and strain gage measurements was used to compute values marked by open circles in the diagram, Figure 3. Considering the small value of stress at the points considered, the relative error of measurement is rather large. There is, however, a general agreement between the two methods employed.

B. Residual stress pattern in the weld. The two most striking features of the stress distribution across the thickness of weld are: 1. the wide difference between the surface stress and the stress in the interior, and 2. the superficial character of the stress gradient. Both features have been found in other types of welds, in particular in the armor welds, as will be shown in the next final report. Therefore, they are not accidental, but constitute a common occurrence in welds. It seems logical to seek their origin in the rate of cooling following the welding operation. But the known fact that the last pass of weld cools down slower than the remainder of the weld deposit cannot be offered as a satisfactory explanation. For this would promote tension and not compression on the surface. Besides, it would not explain the very superficial character of the stress gradient.

To account for the presence of a compression the surface layor of the last pass must cool faster than the interior of the block. This condition can occur only at the very late stage of cooling, probably below 400° F., at which stage the flow of heat through the bulk of metal becomes smallor than the heat losses through the surface. Since tho residual stress pattern is shaped probably not very much above 400° F., it is conceivable that the final value of stress depends primarily upon the conditions of heat flow existing in this range of temperature. This circumstance also would explain the superficial nature of the stress gradient.

In addition to the superficial stress gradient, there is a less pronounced stress gradient on the bottom side of the block No. 11 between the last pass and the other passes of weld. This stress gradient does comply with the condition of a slower rate of cooling of the last pass, sinco it puts the latter in tension. Surprisingly, no such a gradient has been found in the block, No. 8. Yet, according to information this block was a part of a continuous weld, whereas block No. 11 was taken from a step back cascade weld. One would naturally expect a greater difference in the rate of cooling in a continuous weld, than in a step back cascade weld made of small blocks 5" long. It is quite possible that excessive porosity present in the block, No. 8 accounts for this anomaly. In view of this situation, it would seem desirable to duplicate the present work using a more sound weld metal.

Conclusion

In spite of the preliminary nature of the present work, it may be safely concluded that there is real interest in studying the stress distribution across the thickness of welds. The existence of a skin effect revealed by this investigation may have a far reaching effect on both, the methods of exploration and the study of residual stress in practice.

A consistent picture of the stress distribution is obtained across the thickness of weld, when combining the information given by x-rays and wire gage readings according to a method worked out at this laboratory.

There is, however, a need for more work to ascertain the value of this method.

APPENDIX

Section 1: Determination of residual stress across the thickness of blocks by means of wire gage readings.

As pointed out previously two methods were employed to determine the distribution of residual stress across the thickness. Both consisted essentially of removing layers of metal from one face of the block and computing the change thus produced in the remainder of the block. In the first of these methods, wire gage readings were used for the computation of stress in the layers removed by slicing. The procedure was very similar to that used for measuring stress in cold drawn tubing (1).

For the theoretical assumptions and developments underlying the application of this method, reference is made to a publication which will appear shortly (2). In the following only the procedure as used in the present work will be described.

Two electric wire SR4 gages were placed on both faces of the block, one on the top face, one on the bottom face. The gages used in the California Project were saved for this purpose on block No. 11, whereas a new set of SR4-A1 gages was put on block No. 5 to permit preliminary exploration of stress by means of x-rays as explained in section 2.

The blocks were then sectioned in half and from each half of the block slices of metal about 1/8" thick were removed progressing from the midsection toward the outer top or bottom face of the block. The slices were cut using a small band saw, 24 teeth per inch, No. 23 gage and 1/2 inch wide. The cutting operation proved to be of no significant effect on the wire gage readings, at least not before the thickness of the block became substantially smaller than 0.1". To reduce further the thickness, careful grinding followed by etching of the cold work layer was employed.

The change of strain produced on the outer face at each step of the operation was measured and plotted as a function of the thickness remaining after the cut. The results are represented in diagrams, Figures 4 and 5, for blocks No. 11 and 8 respectively. For convenience, plots for the bottom and top gages were combined in one diagram, by using as abscissa the position of the cut in the original block.

From these diagrams the amount of residual stress S relieved by the cut at each section was computed by means of the following formula* (2):

$$S = E\left[-\frac{1}{2}\frac{de_t}{d\alpha}(1-\alpha) + 2(e_t - e^o{}_t) - 3(1-\alpha)\int_{0.5}^{\alpha}\frac{(e_t - e^o{}_t)\,d\xi}{(1-\xi)^2} - e^o{}_t(5\alpha - 4) - e^o{}_b(1-\alpha)\right]$$

This formula applies to the upper half of the block, but the same formula remains valid for the lower half, if the indices t and b are interchanged.

The meaning of the symbols is the following:

E = modulus of elasticity = 30×10^6 psi for steel

α = fraction of the total thickness removed by slicing

e_t or e_b = total change of strain measured on top or bottom gage for the position α, after the block has been split and sliced so that the thickness has been reduced to the fraction $1-\alpha$

$e^o{}_t$ = the change of the top gage, when splitting the block in half,

$e^o{}_b$ = same as $e^o{}_t$ but for the bottom gage, and

* The formula is based on the assumption that there is no stress in the direction perpendicular to S.

$\frac{de}{d\alpha}$ = the slope of the diagram at the corresponding value of α.

As for the integral appearing on the right side of the formula (I), it involves all values of auxiliary variable ξ comprised between 0.5 and α and the corresponding values of e_t. This integration is accomplished graphically.

In the actual application α varies between 0.5 and 1.0. For α = 0.5

$$s_{0.5} = E\left[-\frac{1}{4}\frac{de^o_t}{d\alpha} + \frac{3}{2}e^o_t - \frac{1}{2}e^o_b\right] \qquad \text{(II)}$$

and likewise by interchanging t and b

$$s_{0.5} = E\left[-\frac{1}{4}\frac{de^o_b}{d\alpha} + \frac{3}{2}e^o_b - \frac{1}{2}e^o_t\right]$$

Since both values must be the same, one of these relations may be used as a check, or to correct eventually the somewhat uncertain values of the slope at the beginning of the diagrams.

For α = 1, the term containing the integral becomes indeterminate. By solving the indetermination there follows (2)

$$s_t = -E \times e_t$$

and likewise

$$s_b = -E \times e_b$$

Obviously, the exact value of e for α = 1 cannot be obtained except by extrapolation. The latter procedure becomes quite uncertain, if the stress gradient is very superficial, as is the case in the present investigation. Continuous lines in the diagram, Figures 2 and 3 have been computed by means of the above formulas using results plotted in diagrams Figures 4 and 5.

Section 2. Determination of residual stress by combining x-ray and wire gage readings.

In this method the wire gage readings merely serve to determine a correction term. This term is the change of stress on the newly formed face produced by slicing of the specimen. If, in addition, the actual value of stress is measured on this face by means of x-rays, the original value of stress before slicing is readily obtained by subtracting the change of stress from the stress measured after slicing. For particulars, reference is made again to the previously mentioned publication (2).

The actual measurements of stress by means of x-rays were made only on the bottom half of the block No. 8. But before splitting the block in half, the amount of stress present on both faces also was determined. Since this was done before any relief of stress had occurred, the so determined stress represented the true stress on the surfaces. Wire gages were then attached to both faces and the block was split in half. The newly formed section of the bottom half was polished and etched for x-ray determination. This procedure was followed for the successive sections, distant 0.3, 0.172, 0.145, 0.12 and 0.095 inches respectively from the bottom face. To obtain a representative average, the x-ray determinations were made at three points of the section. The location of the points is indicated in the sketch, Figure 6.

The results of these various determinations are summarized in Table I.

Using average values of stress computed in Table I, diagram, Figure 6 is obtained similar to that represented by Figure 5, except that there are no points for the upper half of the block No. 8. From these two diagrams the true value of stress at each section of the bottom half has been determined by means of the following formula (2).

$$S = S^* - 2(1-\alpha)\int_{0.5}^{\alpha} \frac{S^*\, d\xi}{(1-\xi)^2} + E\left[(e_b - e_b^0) - 2(1-\alpha)\int_{0.5}^{\alpha} \frac{(e_b - e_b^0)\, d\xi}{(1-\xi)^2} - e_b^0(5\alpha - 4) - e_t^0(1-\alpha)\right] \qquad \text{(III)}$$

In this formula all symbols have the same meaning as in formula (I), except for S^* which represents the actual average value of stress measured by means of x-rays at the section α.

By putting $\alpha = 1$, there follows similarly to the formula (II), since S^* becomes zero:

$$S = - E \times e_b \qquad \text{(IV)}$$

The results of computation of stress by means of formula (III) have been plotted as separate circles in the diagram Figure 3 at 0.3, 0.172, 0.145, 0.12 and 0.095 in. from the bottom face. The radius of the circle = 2000 psi, represents the probable error of measurement. As for the end points of the diagram, Figure 3, they are values of stress determined directly on the two faces of the original block No. 8 by means of x-rays as mentioned previously.

A somewhat different procedure was followed to obtain the end points of the diagram Figure 2 referring to the block No. 11. Since it was desired to save the original gages from California, no direct measurements of stress by means of x-rays were made on the two faces before slicing.

After the slicing however, when the two halves were reduced ultimately to some 0.11 in. in thickness, the gages were removed and the balance of residual stress, left on top and bottom face of the block, measured by means of x-rays. If the amount of this stress is called S^*_t and S^*_b respectively then the value of the original stress S_t and S_b, present before slicing is simply:

$$S_t = S_b^* - E \times e_b \qquad (V)$$

and

$$S_b = S_b^* - E \times e_b$$

where e_t and e_b represent the total change of strain recorded by means of wire gages on the face considered. As a matter of check the same procedure was applied to the remaining parts of the block No. 8, and the values computed by means of formula (V) were compared to those determined directly before slicing. In doing so, a correction factor for bending was applied to the values of e_t and e_b to account for the fact that the wire strain gages were located 0.004" above the surface of the block. As shown elsewhere (2), this correction factor may become as high as 7%, if the slicing is carried out below the thickness of 0.1" and if the stress gradient is very steep near the surface. The results of these various measurements are summarized in Table 2.

As seen from this table there is a slight discrepancy between the direct x-ray measurements and the values determined by means of formula (V). The latter are somewhat higher.

REFERENCES

(1) G. Sachs & Van Horn, Metals Technology, Vol. 8, No. 1 (1941) Technical Publication No. 1384.

(2) J. T. Norton & D. Rosenthal, "A Method of Measuring Triaxial Residual Stresses in Welded Plates," Welding Journal, Vol. 24, 1945 (in preparation).

Table 1.

DETERMINATION OF RESIDUAL STRESS BY MEANS OF X-RAYS IN THE

BOTTOM HALF OF BLOCK NO. 5

(For location of points, see sketch, Figure 6)

Section in. from bottom face	Stress in psi at point 1	2	3	average
0.3	- 5,500	- 7,700	- 2,200	- 5,100
0.172	-20,000	-19,000	-21,000	-20,000
0.145	-24,600	-17,000	-14,000	-15,500
0.120	-19,000	-21,000	-23,000	-21,200
0.095	-15,200	-13,200	-26,000	-21,000

Table 2.

Determination of Residual Stress on Top and Bottom Face of Blocks No. 11 & 8.

Face	Thickness of slice	Surface Stress by X-rays after slicing		Total change in Surface strain due to slicing		Original surface stress from formula V	Original surface stress by X-ray
		Point	psi	Meas.	Corr.	psi	psi
Block No. 11							
Top	0.105	1	-43,000				
		2	-38,000				
		3	-31,000				
		Ave.	-37,000	395	380	-48,700	
Bottom	0.120	1	-44,000				
		2	-47,500				
		3	-25,000				
		Ave.	-38,000	500	480	-53,000	
Block No. 8							-17,000
							-41,500
Top	0.075	1	-36,000				-34,500
		2	-34,000				
		3	-30,000				
		Ave.	-33,000	480	440	-46,200	
Bottom	0.075	1	-24,000				-43,700
		2	-39,000				-45,600
		3	-33,000				-43,000
		Ave.	-32,000	600	550	-48,500	

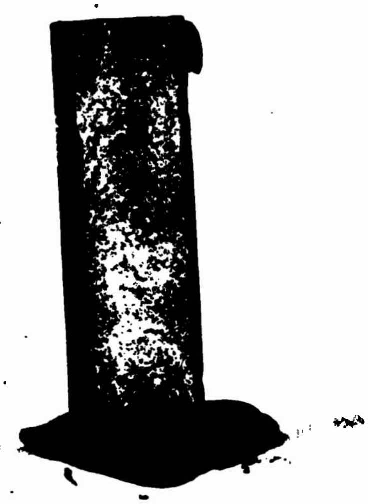

Figure 1. Small Cracks in Block No. 8, 0.2" Below the Top Surface. Magnification 2x

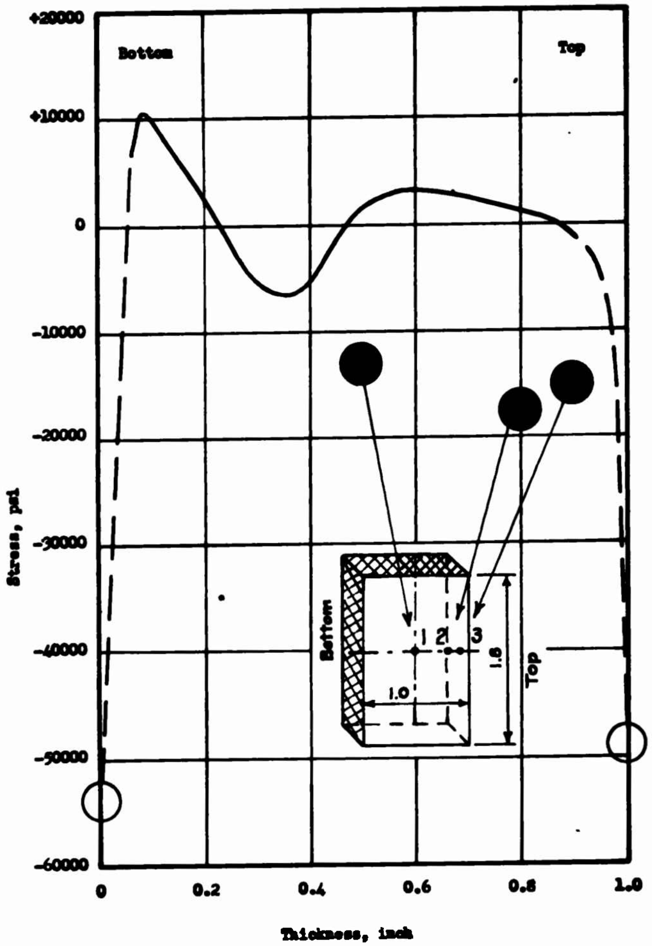

Figure 2. Block No. 11. Step back cascade. Distribution of residual stress across the thickness.

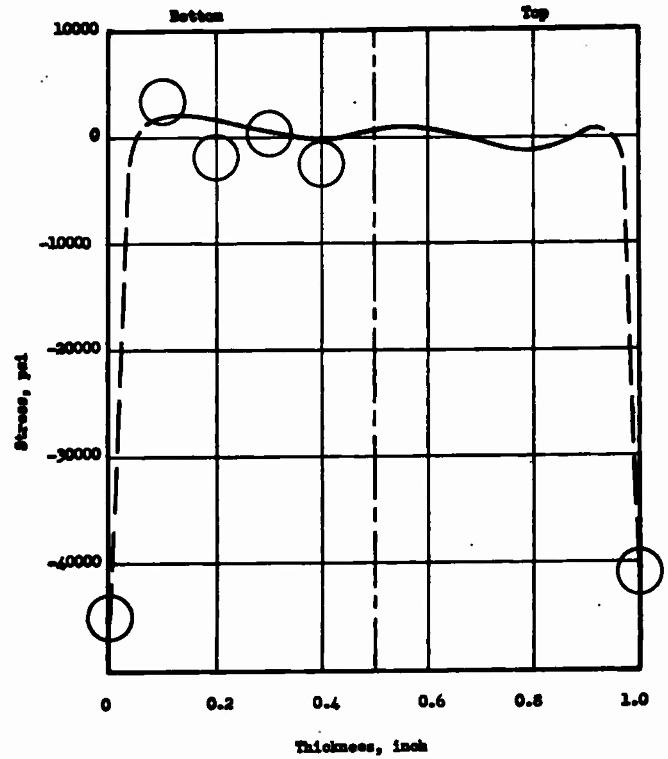

Figure 3. Block No. 8. Continuous welding. Distribution of residual stress across the thickness. Continuous line = wire gage measurements, open circles = X-ray measurements.

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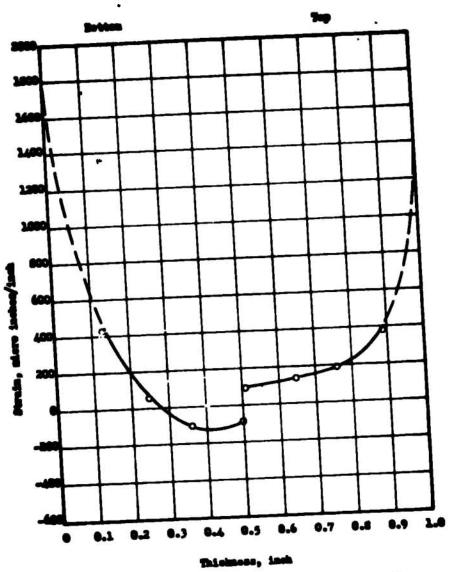

Figure 4. Block No. 11. Step back cascade welding. Change of strain produced on top and bottom face by splitting and progressive slicing of the block.

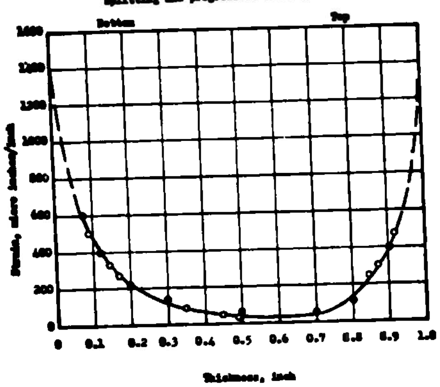

Figure 5. Block No. 8. Continuous welding. Change of strain produced on the top and bottom faces by splitting, slicing and etching away layers of the block.

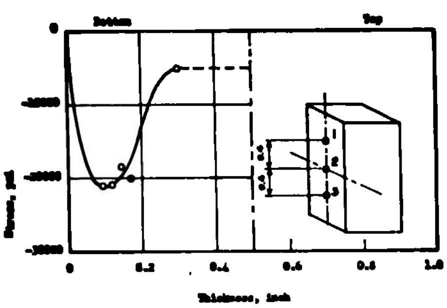

Figure 6. Block No. 8. Continuous welding. Amount of average residual stress determined by means of X-rays at the sections indicated.

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TITLE: Effect of Locked Up Stresses on Ballistic Performance of Welded Armor: Investigation of the Stress Distribution across the Thickness of Weld

AUTHOR(S): Norton, John T.; Rosenthal, D.; Maloof, S. B.
ORIGINATING AGENCY: O.S.R.D., N.D.R.C., Div. 18, Washington, D. C.

DATE	DOC. CLASS	COUNTRY	LANGUAGE	PAGES	ILLUSTRATIONS
Nov '44	Restr.	U.S.	Eng.	35	photo, tables, graphs

ABSTRACT:

P1914, Armor Plate, Welded Joints

Detailed study is presented of the residual stress pattern through the thickness of armor plate in the neighborhood of the weld, using the welded armor as well as low carbon plate which is better suited to the X-ray method. Investigation was limited to low carbon weld for which satisfactory X-ray stress determination could be made. Results reveal a marked skin effect in the distribution of residual stress across the thickness of weld.

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TITLE: Effect of Locked Up Stresses on Ballistic Performance of Welded Armor (OD-(106): Investigation of The Stress Distribution Across The Thickness of Weld

AUTHOR(S): Norton, J. T.; Rosenthal, D.; Maloof, S. B.

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over

ABSTRACT:

A detailed study is made of the residual stress pattern through the thickness of a welded low carbon plate to obtain some idea of the stress pattern in armor plate welds. The cross-section of the plate was studied by X-ray and wire gage measurements according to a method worked out by the laboratory. In spite of the preliminary nature of the present work, it may be safely concluded that there is real interest in studying the stress distribution across the thickness of welds. The existence of a skin effect revealed by this investigation may have a far reaching effect on both the methods of exploration and the study of residual stress in practice.

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